A COMPARISON OF NON-INVASIVE GEOPHYSICAL METHODS FOR MAPPING NEAR-SURFACE VOIDS

By

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ABSTRACT

To accurately and economically locate near-surface voids that may impact highway stability, the Central Federal Lands Highway Division (CFLHD), Federal Highway Administration (FHWA) in coordination with Blackhawk GeoServices investigated a variety of geophysical techniques at the Lava Beds National Monument (Monument). The main objectives were to; **(a)** detect the presence of subsurface voids under specific geologic settings, **(b)** detect and characterize the vertical/horizontal extent of voids, **(c)** determine the most economical and time effective geophysical method(s) for utilization during roadway site investigations, and **(d)** identify the range of applications of such methods nationwide.

Surface geophysical surveys utilizing several methods were applied at the Monument over several known lava tube caves to determine the most effective method(s) for delineating subsurface voids in a semi-controlled investigative setting. Data were collected using ground penetrating radar (GPR), magnetic, electrical resistivity (ER), and high-resolution shear wave reflection (HRSW), geophysical methods. Each selected site had known underground void geometries and locations.

The results of the investigation indicate that some of the geophysical methods were effective in detecting voids, while other methods were limited due to the localized geological setting and void geometries. Depending on each site-condition such as geologic setting, voids size and depth when a combination of methods is used, they are effective in delineating the location and orientation of the voids. The GPR and magnetic methods when combined were the most economical and least time consuming in detecting voids to a depth of 0 to 9 m (0 to 30 ft). Magnetic surveys may be performed first to rapidly obtain data over large areas, while the GPR surveys would follow in areas of concern to determine the depth and size of subsurface voids.

This paper presents general information about the site geology, survey site descriptions, overview of the geophysical methods utilized, data acquisition parameters, and interpretations. The results of this study will be of interest to contractors and construction crews conducting work in areas where subsurface voids may exist.

INTRODUCTION

This paper describes the procedures and results of recent surface geophysical surveys performed at the Lava Beds National Monument located in Siskiyou County, California (Meglich et al, 2003). The main objective of the investigation is to determine the most effective geophysical imaging technology for delineating voids that may pose a threat to road construction and heavy equipment working above them.

The Monument contains several hundred lava tubes from over 30 separate flows making it the largest concentration of lava tubes in the continental United States (Dorman, 2003). The Monument resides within the extensive flood basalts of the Modoc Plateau in northern California. Bounded by the volcano-laden Cascade Mountain Range to the west and the northern extremes of the Sierra Nevada to the south, this broad volcanic plateau extends northward across Oregon, and fades eastward into the Basin and Range of northern Nevada (figure 1). Covering hundreds of square miles, the flood basalts of the Modoc Plateau are among the youngest of the immense flows occurring globally in the past 250 million years. Locally, the Monument is located on the northeast side of Medicine Lake Volcano – an enormous shield volcano that initially erupted nearly two million years ago, with at least six different eruptions from four distinct vents occurring in the last 2,000 years (Alt and Hyndman, 2000).

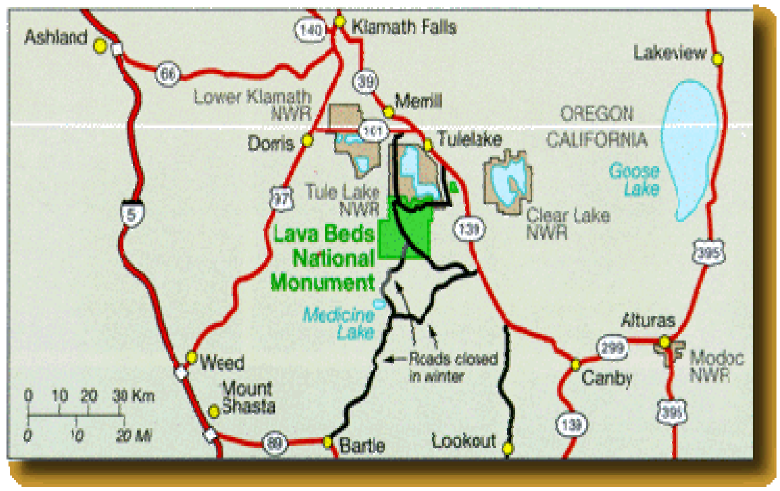


Figure 1. LBNM (Monument) Location Map

Essentially, there are two different types of lava tubes in the Monument. First, “surface tubes” are created when the top and sides of the lava flow cool due to their exposure to the air. This cooled lava solidifies creating a hard cast surrounding the flowing lava, which may then be covered by subsequent flows. Generally, only a few meters in diameter, surface tubes are abundant at the Monument. The second type of lava tube is formed when lava flows down a pre-existing channel, such as a riverbed or a depression. The roof of the lava, exposed to air, cools and hardens forming the eventual tube roof. Such tubes can be quite large, with many at the Monument exceeding 15 m (50 ft) in diameter. In both cases, the lava tube eventually drains to become a subsurface void, filled with air, water, or collapsed overburden. It is also common for tubes to be stacked one atop the other, often connected by intervening “skylights”.

Geophysical surveys were conducted in the vicinity of Cave Loop Road in the southern end of the Monument at three locations; *Indian Well Cave, Golden Dome Cave, and Hercules Leg Cave* (figure 2). Two other locations, *Merrill Cave* approximately 3 kilometers northwest of the Visitor’s Center, and *Monument Road Cave* along Hill Road near Devil’s Homestead Flow were also investigated.

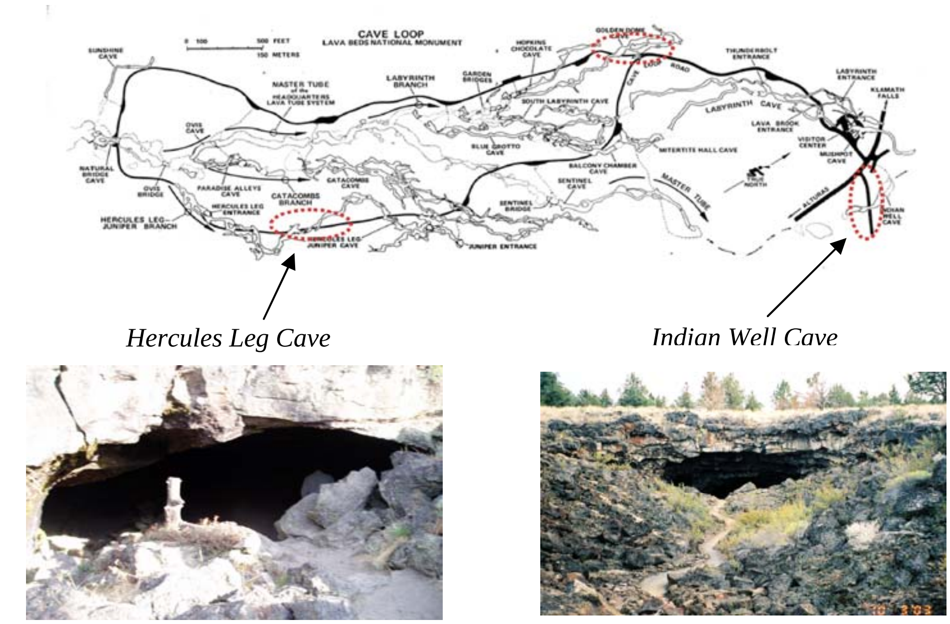


Figure 2. Map of Cave Loop Road showing geophysical survey areas (outlined in red).

DATA ACQUISITION

Currently, a variety of geophysical techniques exist to locate subsurface voids. Each method has limitations in depth of exploration and resolution accuracy based on geological settings, target (void) size and orientation. To determine the advantages and limitations in a semi-controlled investigative setting, several geophysical methods were used to collect data over several known cave locations. The following four geophysical methods were used in the survey:

- Ground Penetrating Radar (GPR);
- Magnetic Method;
- Electrical Resistivity (ER);
- High Resolution Shear Wave (HRSW) Seismic Reflection.

Although other methods such as microgravity have shown success for detecting voids, the above methods were selected because of their fast acquisition rates and cost-effectiveness.

Ground surveys were performed using a Differential Global Positioning System (DGPS) and other surveying instruments to; (a) locate geophone and survey line start and end points, (b) record elevation points, and (c) to record cave openings, estimated cave locations, and road location coordinates. Additionally, sensor positioning for the magnetic data were obtained in real time using the DGPS carried by the magnetometer operator. Table 1 summarizes the overburden thickness, void width and height of the surveyed caves, and geophysical methods used.

Table 1. Geometries of surveyed voids, and the geophysical methods used.

Subsurface Voids	Overburden Thickness m (ft)	Void Width Under Road m (ft)	Void Height Under Road m (ft)	Geophysical Methods
Monument Road Cave	5.5 (18)	12 (40)	5.5 (18)	GPR, Magnetic, ER, HRSW
Indian Well Cave	8.8 (29)	7.9 (26)	8.5 (27.8)	GPR, Magnetic, ER, HRSW
Golden Dome Cave	4.0 (13)	3.8 (12.5)	2.6 (8.8)	GPR, Magnetic, HRSW
Hercules Leg Cave - North	3.3 (10.7)	9.8 (32)	0.8 (2.5)	GPR, Magnetic, ER, HRSW
Hercules Leg Cave - South	2.7 (8.7)	22.3 (73)	2.4 (8)	GPR, Magnetic, ER, HRSW

In this manuscript, selected geophysical data from selected cave locations only are presented. A complete report of this is available from the CFLHD, FHWA, Denver, CO. The following sections present a summary of the geophysical methods used, data acquisition, and data analysis and interpretation at each selected void site.

Method 1: Ground Penetrating Radar – This method can be used to locate shallow voids. Depth of penetration is dependent on the geologic setting and target size, in particular the ground conductivity. As the GPR system is towed along the ground surface, electromagnetic waves are transmitted into the ground and are reflected from boundaries and objects that have different electrical properties (dielectric constant). An air-filled void, as in the case of lava tubes, will provide a dielectric contrast with the host rock.

Three lines of GPR data were collected over the road at four separate sites using the SIR-2000 system, as shown in Figure 3. The survey lines were spaced 1.2 to 1.5 m (4 to 5 ft) apart and about 50 to 104 m (164 to 340 ft) long. The SIR-2000 control unit was setup in the back of a vehicle, while a cable connected it to the antenna. Two different frequency antennas, 200 and 400 MHz, were utilized at *Monument Road, Indian Well, Golden Dome, and Hercules Leg Caves*.

Figure 3. GPR data collection a Hercules Leg with the 400MHz antenna and survey wheel

Method 2: Magnetic Methods – The magnetic method works by mapping variations in the magnetic field. The Geometrics G858 Magnetometer (G858) was used to measure the Earth's total magnetic field that is a summation of the anomalous fields and the background field of the earth (including diurnal variations). When the background field is subtracted from the total field, the anomalous field is determined. The anomalous field may be used to identify potential voids. Included in the anomalous field is the remnant magnetization of the basalt. Over a void, where there is a lack of basalt and therefore lack of remnant magnetization, there will be a decrease in the measured magnetic field. Depending on the orientation of the remnant magnetic field in the basalt and the orientation of the present day magnetic field, a void could appear as either a magnetic high or low in the total field magnetic data.

Three lines of data using one magnetometer sensor were collected at each site (figure 4). The magnetic data were collected along either side of the road and down the center of the roadway with approximately 1.5 to 2.1 m (5 to 7 ft) line spacing at each site. Magnetic data were recorded at 10 Hz (10 times per second) and coupled with a DGPS for positioning. To correct the magnetic data for diurnal variations, base stations were established at the *Indian Well Cave* and *Monument Road Cave* sites.

Figure 4. Magnetic data collection using the G-858 Magnetometer at Monument Road Cave.

Method 3: Electrical Resistivity – This method measure the apparent resistivity of the subsurface. The depth of investigation is a function of the array type and the electrode spacing. As the distance increases between the current and the potential electrodes, the depth of investigation increases.

The Electrical Resistivity (ER) method has been successful in locating voids when there is a resistivity contrast between the void and the surrounding host rock. Water-filled voids, depending on salt content and acidity, have resistivities ranging between 40 and 500 ohm-m, whereas, air-filled voids are highly resistive with values ranging from thousands to several tens of thousands ohm-m. In the case of the lava tube, if the cavity is filled with water, data interpretation of voids may be difficult because the difference between the resistance of the host rock and the resistance of the water-filled void may not vary enough to register.

The field survey for this method is usually quite labor intensive and time consuming, especially in areas of hard rock where electrodes may need to be pounded into the ground. Advances in technology have generated arrays that are capacitively coupled and are towed along the ground by a single operator (figure 5).

Data were collected with the OhmMapper TR2 along the roads at the *Monument Road, Indian Well, and Hercules Leg Caves*. The array consists of two receiver electrodes and one transmitter electrode. The transmitter and receivers are separated by non-conductive rope which determines the depth of investigation. Two ropes with lengths of five and ten meters were used.

Figure 5. ER data collection using the OhmMapper TR2.

Data collection began in a stationary mode with the center of the non-conductive rope at a known location. The data were collected manually by towing the array at all locations, as shown in Figure 5. The data were recorded at 2 Hz with marks placed in the dataset at points marked on the road. These points, termed fiducial marks, were later surveyed with the DGPS.

Method 4: High-Resolution Shear Wave – This seismic method can be divided into two categories based on the type of seismic energy used; compressional waves (P-waves) and shear waves (S-waves). Particle motion for P-waves is parallel with the direction of propagation. Particle motion in S-waves is perpendicular to the direction of wave propagation. An important feature of shear waves is that, unlike P-waves, they will not propagate through liquids or gases, as these materials have no shear strength. This makes shear waves particularly valuable for the detection of subsurface water-filled or air-filled voids.

Figure 6. HRSW seismic data collection using the MicroVibrator and LandStreamer system at Golden Dome Cave.

HRSW seismic reflection data were collected using the MicroVibrator and LandStreamer system at *Monument Road, Indian Well, Golden Dome, and Hercules Leg Caves*. Survey lines ranging from 58 to 92 m (190 to 300 ft) were established. The LandStreamer consisted of 96 geophones spaced at 0.61 m (2 ft) intervals and was laid flat on the road in a straight line, as shown in figure 6. The MicroVibrator, used as the seismic source, was then positioned adjacent to the LandStreamer and between geophones, in a configuration known as "shooting on the half station" or in a "symmetric split spread" configuration.

DATA INTERPRETATION

Method 1: Ground Penetrating Radar – In general, voids in the subsurface are visible in the GPR profiles in the form of reflection and/or diffraction hyperbolas (i.e. upside-down U or V shaped features in the profile). In the case of the lava tubes detection at the Monument, the voids are expected to be irregularly shaped due to a highly uneven rock-void interface. This will cause the lava tubes to manifest as diffraction hyperbolas at the rock-void interface in the GPR profiles. The GPR profiles obtained at the Monument show numerous diffractions and diffraction hyperbolas. The GPR signal is scattered by voids, fracturing, inclusions, and other inhomogeneities in the rock and provides detailed subsurface information, but a difficult profile to interpret. The lava tubes are clearly evident at some locations and are obscured by numerous diffractions or depth at others. Deeper lava tubes may also be obscured in the GPR profile by other lava tube. Multi-layer systems are common throughout the Monument.

GPR profiles are displayed in a line scan grayscale with horizontal and vertical axis indicating the length and depth in m (ft). A relative dielectric permittivity of $\varepsilon_r = 8$ was used to calculate depth. The vertical scale is slightly exaggerated for clarity. Interpreted sections are provided with known caves highlighted in blue and geophysical anomalies "unknown caves or suspected caves" highlighted in red. To simplify the discussion, data using the 200 MHz antenna only was selected for the interpretation of the results. Figure 7 displays the GPR data profiles obtained at the *Monument Road, Indian Well, Golden Dome, and Hercules Leg Caves*. The known lava tubes at Hercules Leg were the most readily identifiable lava tubes in all of the GPR profiles at the Monument. The voids are clearly evident in the processed GPR data. This is primarily due to the small amount of overburden present and possible lack of fracturing and blistering in the rock surrounding the *Hercules Leg Cave*. As indicated in table 1, the surveying estimated 2.7 m (8.7 ft) of overburden at *Hercules Leg South Cave* and 3.3 m (10.7 ft) of overburden at *Hercules Leg North Cave*, compared to 2.0 and 1.8 m (6.5 and 6.0 ft), respectively, of interpreted overburden from the GPR Line 1 profile. The width from the surveying was estimated 22.3 m (73 ft) for *Hercules leg South* and 9.8 m (32 ft) for *Hercules Leg North*. Width from the GPR profiles is estimated at 21.3 m (70 ft) for Hercules South and 12.2 m (40 ft) for Hercules North. As shown in figure 7, a third lava tube has been interpreted from the data and is displayed along with the known caves. This anomaly is slightly deeper, approximately 2.3 m (7.5 ft), and smaller in width than the two known tubes.

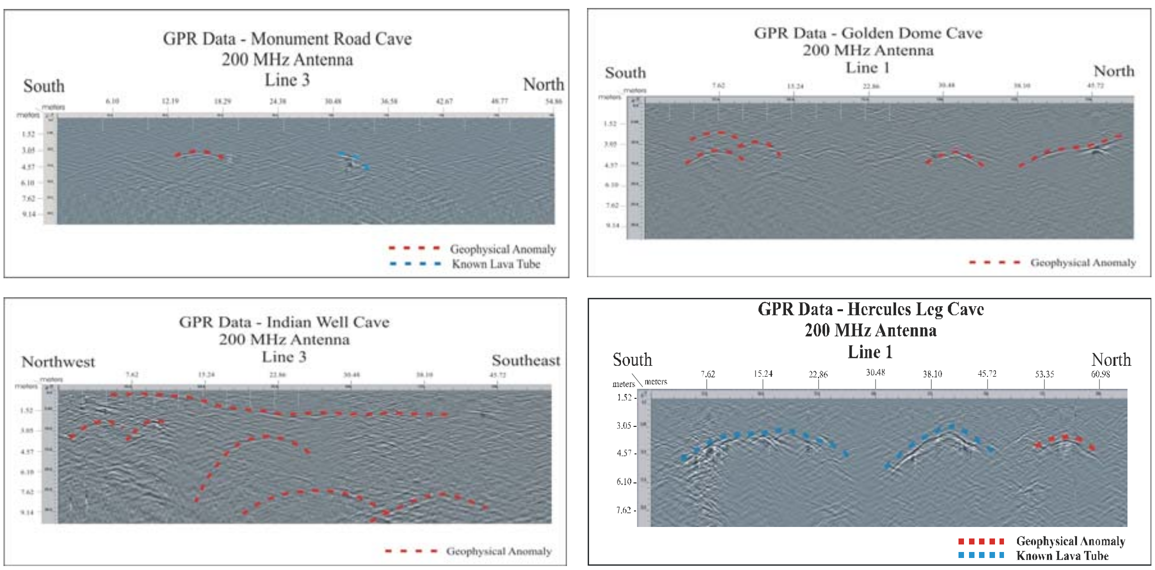
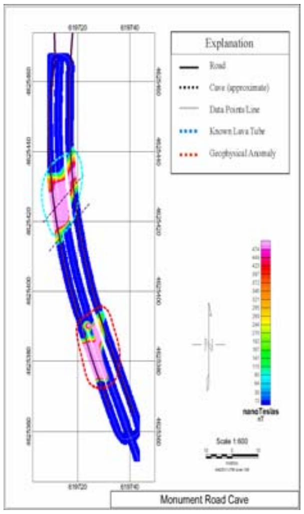
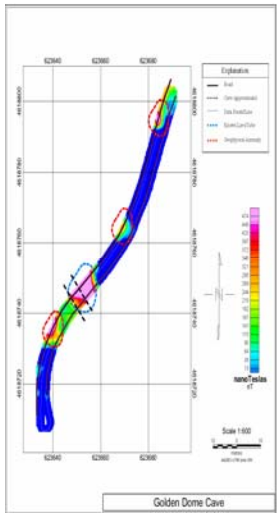


Figure 7. GPR profiles over Monument Road, Indian Well, Golden Dome, and Hercules Leg Caves using 200 MHz antenna. Known caves are outlined in blue while additional geophysical anomalies (unknown caves) are outlined in red.

Method 2: Magnetic – To better explain the magnetic data and understand its results, a Gravity/Magnetic Modeling Software package was used to create a "forward model" with different hypothesis. The best fit model, where magnetic highs are evident over known void locations, depicted a roofed type cave, which is the anticipated type of cave in the Monument.





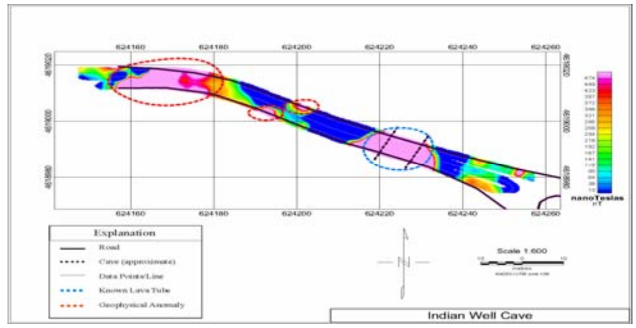


Figure 8. Magnetic data plan view maps over Monument Road, Indian Well, and Golden Dome Caves. Known caves are outlined in blue while additional geophysical anomalies are outlined in red.

With this information in mind, other large areas of magnetic highs were selected as anomalous in the data. Highs in magnetic data are shown as bright pink, while lows are shown as dark blue. All magnetic data are displayed in nanoTeslas (nT). Figure 8 displays the magnetic data plan view maps obtained at *Monument Road, Indian Well, and Golden Dome Caves*. *Monument Road Cave* was successfully located using the magnetic method. A strong magnetic high (approximately 1200 nT), is evident over the known location of the cave. The magnetic anomaly crosses the road at an angle that matches the measured orientation. A second possible cave is interpreted to be 46 m (150 ft) south of the known cave. This anomaly is outlined in red and has a peak reading of approximately 1500 nT, which decreases rapidly from the southwest side to the northeast side of the road. This anomaly has approximately the same orientation as the known cave.

The magnetic data collected over the other cave sites show magnetic highs over the known caves as well as geophysical anomalies that might indicate possible voids (figure 8). These anomalies are possibly individual voids or represent a section of larger caves.

The following section presents the results obtained from the electrical resistivity and the high-resolution seismic collected over the *Indian Well Cave*.

Method 3: Electrical Resistivity – Basalt formations with many air-filled vesicles would have higher resistivity values than solid basalt formations. Additionally, areas with multiple fractures would also produce a higher resistivity value. When viewing or interpreting resistivity data, it is important to understand equivalence. Equivalence allows for multiple inverse models to be interpreted from a single data profile. Although smaller features and the position of the edges of larger features may be distorted, the overall geoelectric section should remain consistent.

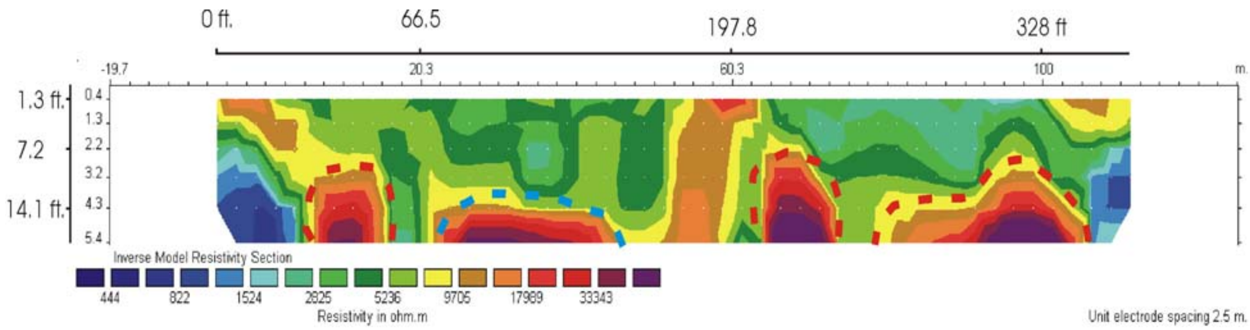


Figure 9. Electrical resistivity profile over Indian Well Cave (known cave is outlined in blue while additional anomalies are outlined in red).

The color scale for the resistivity figure ranges from blue for areas of low resistivity (indicative of solid material) to maroon for areas of high resistivity (indicative of void). Figure 9 displays the data collected at *Indian Well Cave* in the south to north direction.

The data at this site were repeatable in both directions. The background resistivity values for this site are between 1,500 ohm·m and 5,000 ohm-m. The peak resistivity value, 48,000 ohm-m, of the known cave (outlined in blue) is located at 32.17 m (105.5 ft) at a depth of 5.4 m (17.9 ft). This depth is 3 m (10 ft) less than the depth to the top of the cave estimated from the chain and compass surveying. This error is due to the lack of data below 5.4 m (17.9 ft). Since the cave appears as a half circle, with the other half of the circle below the collected data, it is difficult to predict the true depth or height of the cave. The estimated width of the cave is 6.1 m (20 ft), which is close to the surveyed width of 7.9 m (26 ft). There are three other areas of high resistivity (> 28,000 ohm-m) at *Indian Well Cave* site. All three anomalies, outlined in red, appear as half circles along the bottom edge of the graph. To identify the vertical extent of these anomalies interpreted as lava tubes, it would be necessary to conduct additional surveys using longer non-conductive towrope lengths.

Method 4: High-Resolution Shear Wave – The HRSW data are displayed as profiles in a wiggle trace/variable area format. These sections are unmigrated, and the vertical scale is in milliseconds (ms). Shot point number and distance (meters and feet) are displayed along the top of the section. The brown shading on the profiles is a derived seismic attribute known as Amplitude Envelope, calculated from the Hilbert Transform of each trace. The Amplitude Envelope display is used to enhance steeply dipping events on the seismic data. Note that for this seismic profile, 1 ms is roughly equivalent to 0.61 m (2 ft).

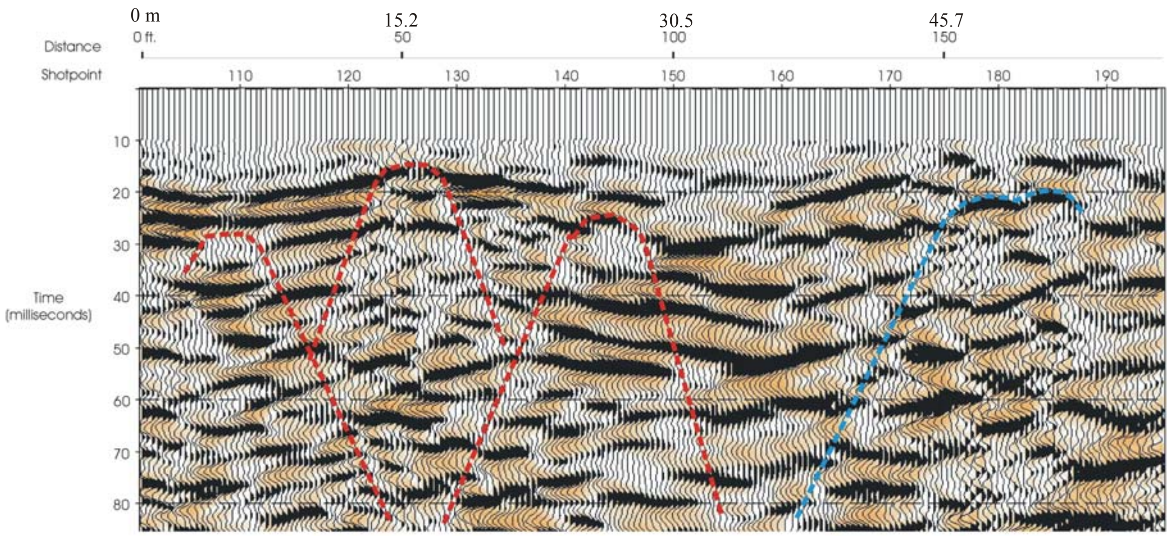


Figure 10 – HRSW profile over Indian Well Cave (known cave is outlined in blue while additional anomalies are outlined in red). (Note: the HRSW and TR2 data were collected in reverse direction and have been displayed that way).

An interpreted HRSW section over *Indian Well Cave* is illustrated in Figure 10. Zero time is at an elevation of 1,436 m (4,710 ft). The known cave beneath this profile is centered at shot point 180 and extends about 4 m (13 ft) on either side of this point. The stacking velocity in the vicinity of the known cave is approximately 1,357 m/sec (4,450 ft/sec, and the expected overburden is approximately 8.8-m (29-ft) thick. The reflection from the top of this lava tube should occur 13 ms below the start of data (the ground surface is at 10 ms on this line). A reflection event is evident at this level, with a zone of disturbed seismic reflectors underneath it. A fairly strong diffraction, made evident by the Amplitude Envelope portion of the display, slopes down from the left (west) edge of the lava tube.

A suspected lava tube occurs at shot point 126 outlined in red, and appears to be approximately 3.7 m (12 ft) across. This anomaly originates about 4 m (13 ft) below the ground surface, and is evidenced by an arcuate reflection event overlying a zone of low amplitudes bounded on either side by diffractions. Two other suspected caves, outlined in red are centered on shot points 109 and 144, respectively.

CONCLUSIONS AND RECOMMENDATIONS

The lava tubes profiled at Lava Beds National Monument manifest themselves in each of the geophysical methods used. However, each of the lava tube sites has unique aspects with regard to data collection and interpretation. Due to page limitations, only significant results of this investigation are presented:

- **Method 1: Ground Penetrating Radar** – Although there are numerous diffractions in all of the GPR data sets, only data collected over *Hercules Leg Cave* defines the extent and depth of the lava tubes. The GPR method was effective at detecting voids down to depths of 4.0 m without “calibration”. The GPR may be a more practical method for determining shallow void characteristics where individual anomalies are not distinguishable by the other methods.

- **Method 2: Magnetic** – The magnetic method proved successful in detecting/locating three of the four known lava tubes at different sites. Magnetic data collection, processing and interpretation were proven to be quick and economical, covering large areas.
- **Method 3: Electrical Resistivity** – The ER method was successful in detecting lava tubes at each of the investigated site. Data collection proved difficult in confined areas or on single lane roads where tight curves exist in the road.
- **Method 4: High-Resolution Shear Wave** – The HRSW data identified each of the known caves in each profile. The processing and interpretation stages were aided by knowing the approximate location of each lava tube. This method defined the extent and depth of each known cave. Although the deployment of the method is more costly, it is effective in determining voids with more than 3.0 m of overburden. The method should be used in conjunction with another geophysical method or in area where the processing and interpretation may be calibrated over a known lava tube.

Overall, each known lava tube was detected with at least two geophysical methods. The ease in data acquisition using the magnetic or ER makes them more favorable methods for lava tube detection at the Monument. Anomalies interpreted from these two methods, may then be further investigated using the HRSW or GPR method. The GPR method may be a more practical for determining shallow void characteristics where individual anomalies are not distinguishable in the other methods.

It is recommended that the magnetic or ER surveys be conducted first to rapidly obtain data over large areas. These surveys are easily deployed, have high collection rates, and the data may be processed within short periods of time. It is also recommended that GPR survey will follow in areas of concern to more accurately determine voids geometry. The combination of these methods is the most economical and reliable in detecting subsurface voids.

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